Atomic Clocks:

Precision time-keeping and fundamental physics

Benjamin M. Roberts

University of Queensland, Australia

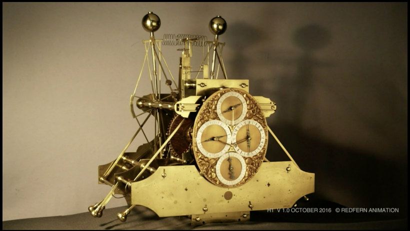
18 July 2022

A clock is a thing that ticks

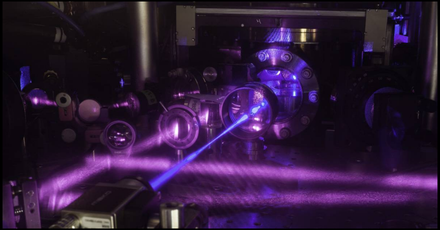
Periodic predictable motion: count ticks

- Earth's orbit/rotation
- Flowing water/sand
- Swinging pendulum
- Oscillating electromagnetic wave

Getty



H1 (Royal Museums Grenwhich)



JILA

Precision timing: long history of fundamental physics/astronomy

1657: Huygens designs pendulum clock

- Accurate to $\sim 15\,\mathrm{s/day}$
- Works on solid physics principal: $T \propto \sqrt{L}$

1672: Jean Richer expedition to French Giana

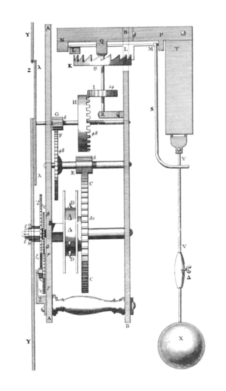
- Observe Mars near equator – measure scale of solar system
- Failed: pendulum clocks ran slow by $2\,\mathrm{min/day}$

1687: Newton's Principia (15 years post Richer)

- Explained Richer's measurement: law of gravitation

1676: Rømer calculates speed of light

- Observe eclipse of Jupiter's moons
- Required accuracy of $\sim 30\,\mathrm{s/day}$



Huygens 1673

$$T = 2\pi\sqrt{\frac{L}{g}}$$

Universal frequency standard

- Pendulums (+all kinematic clocks): depend on materials, location, specifics
- Earth rotation: unstable $\sim$5 ms/day (10^{-7})

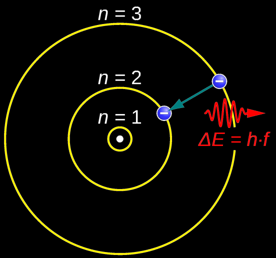
Lord Kelvin in 1879 (attributed to Maxwell):

> *The recent discoveries due to the kinetic theory of gases and to spectrum analysis indicate to us natural standard pieces of matter such as* **atoms of hydrogen or sodium, ready made in infinite numbers, all absolutely alike in every physical property**. *The time of vibration of a sodium particle corresponding to any one of its modes of vibration is* **known to be absolutely independent of its position in the Universe**...

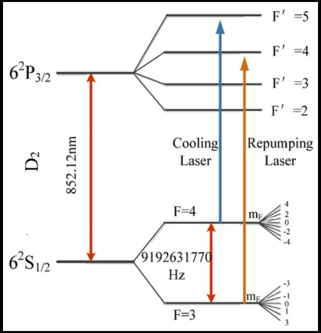
Thomson, W., and P. G. Tait, 1879, Elements of Natural Philosophy (Cambridge University Press, Cambridge, England).

Atomic frequency standard

- Atoms: absorb/emit specific frequencies
- Universally constant

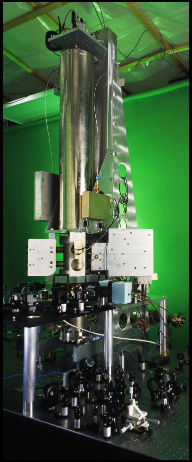


JabberWok/Wikipedia



Cs Hyperfine Structure

NIST F1:
Cs fountain clock



NIST, Geoffrey Wheeler

1967: ^{133}Cs hyperfine transition: $f_0 \equiv 9,192,631,770\,\text{Hz}$
NIST F1: Accurate to ~ 10 ns/day (3×10^{-16})

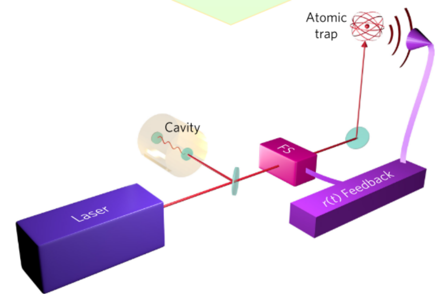
Atomic clocks: basic principal

“Thing that ticks”: external oscillator

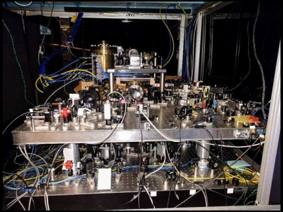
- Microwave cavity
- Electric field of laser light (optical clocks)
- Even quartz oscillator (e.g., GPS clocks)
- Typically: better short-term stability than atomic transition
- But: depend on external conditions

Oscillator kept on resonance with atomic transition

- Monitor atomic transition
- Send correction signal: adjust oscillator



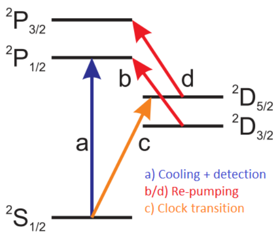
Wcislo 2016



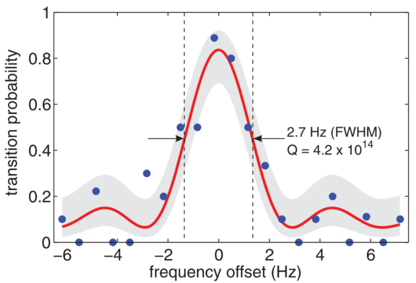
Ye, UC Bolder

Clock operation: some considerations

0. Cooling/trapping/confining
1. State preparation: Ensure atoms in state $|A\rangle$
2. Interrogation: excite clock transition $|A\rangle \to |B\rangle$
3. Detection: measure population of $|B\rangle$



Ludlow 2015

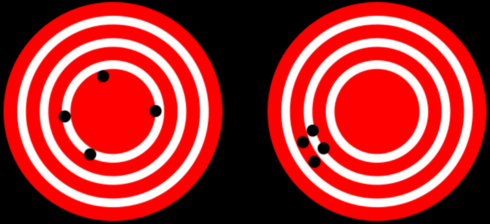


Chou 2010

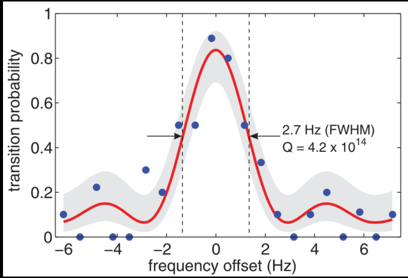
- Drive clock transition $|A\rangle \to |B\rangle$: $\omega = \omega_{AB} + \Delta$
- Maximise transition rate, Γ: minimise detuning $\Delta = 0$
  - $\delta\Gamma/\delta w$: maximum near half-maximum
  - absorption/stimulated emission: state preparation
- Observe population of $|B\rangle$: $\propto \Gamma$
  - $|B\rangle \to |C\rangle$, observe fluorescence from $|C\rangle$
  - Shelving/quantum amplification

Accuracy, precision, stability

- Atomic transition: "perfect" accuracy
- Ultra-stable laser: high precision, poor accuracy
- Accuracy of clock: **depends on time-scale**
- Averaging time: τ



DarkEvil/Wikimedia Commons



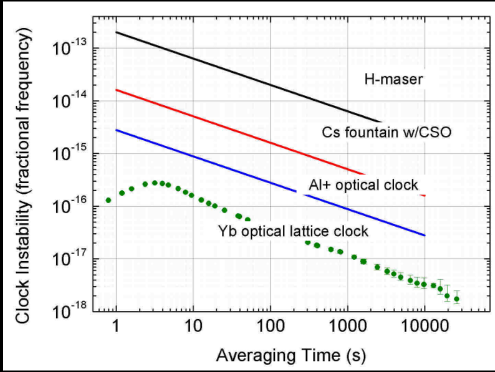
Chou 2010

- If limited by quantum projection noise:

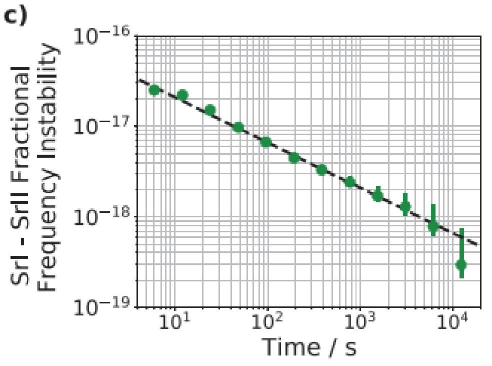
$$\sigma_y(\tau) = \frac{\delta f}{f_0 \sqrt{N}} \sqrt{\frac{T_{\text{cycle}}}{\tau}}$$

- This example: Al^+ clock: $f_0 \approx 1121.02\,\mathrm{THz}$

Allan deviation: clock precision



SYRTE/NIST



JILA

- Optical clock: 10^{-18} – 1 s /100 Billion yrs
- Earth rotation: 10^{-7} – 1 s / year
- Quartz: 10^{-7} – 1 s / year
- Mechanical watch: 10^{-5} – 1 s / day

Example: Gravitational red-shift

Gravitational red-shift: from General relativity

$$\frac{\delta f}{f} = -\frac{\delta U}{c^2} \sim 10^{-16}\,\frac{\delta r}{1\,\mathrm{m}}$$

Easily detectable by modern optical clocks:

$$\frac{\delta f}{f} \sim 10^{-18-19}$$

- Cornerstone of modern geodesy / reference systems
- Gravitational red-shift is one of the biggest systematic which must accounted for in clock comparisons – even within the same lab!

Compare to frequency shift of pendulum clock: $f \propto \sqrt{g/L}$:

$$\frac{\delta f}{f} = -\frac{\delta r}{r} \sim 10^{-7}\,\frac{\delta r}{1\,\mathrm{m}}$$

Fundamental Physics

Standard Model + General Relativity

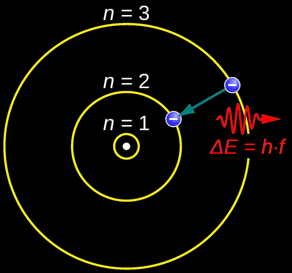
- Extraordinarily successful: however, incomplete
- Quantum gravity, matter–anti-matter asymmetry, dark matter/energy etc.

Precision time-keeping as probes of fundamental physics

- Search for evidence of *new physics*
- Variation of fundamental constants (just a few examples)
- Also: tests of GR, LLI, CPT symmetry stc.

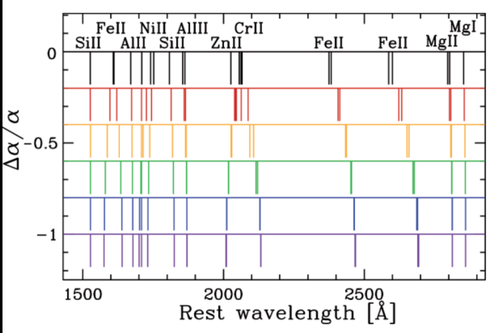
Variation of Fundamental Constants

- Are the laws of physics the same everywhere/when in the universe
- Atomic energies, and thus frequencies, depend on **fundamental constants**
- Each transition depends differently on constant: K must be **calculated**
  - e.g., Fine structure constant: $\alpha \approx 1/137.036...$ (strength of electromagnetic force)



JabberWok/Wikipedia

$$\frac{\delta f}{f} = K \frac{\Delta\alpha}{\alpha}$$



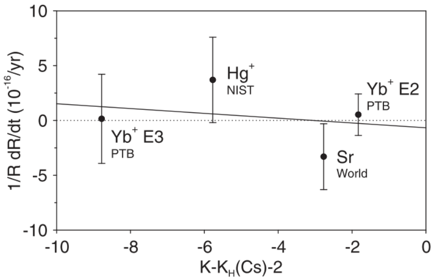
Murphy 2012

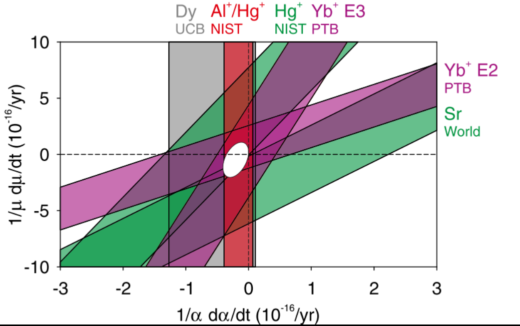
Temporal variation

- Observe multiple clocks over long time periods
- Different sensitivity to α, $\mu = m_e/m_p$

$$\frac{\delta\alpha}{\alpha\,\delta t} = -0.2(2) \times 10^{-16}/\mathrm{yr}$$

$$\frac{\delta\mu}{\mu\,\delta t} = -0.5(1.6) \times 10^{-16}/\mathrm{yr}$$

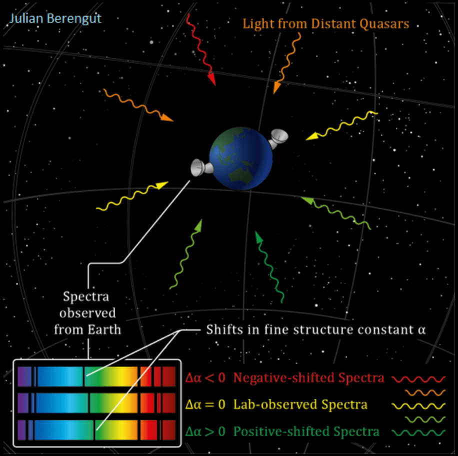


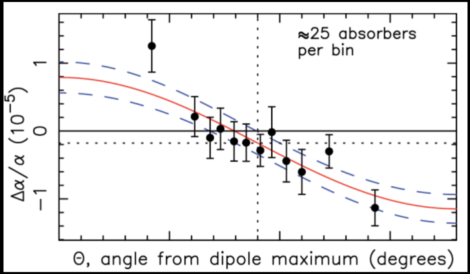


- Huntemann *et al.*, PRL **113**, 210802 (2014)

Spatial variation: Australian dipole

- Observe spectra from distant stars
- Compare to measurements on Earth





Murphy 2012

- non-zero gradient ($\sim 3\sigma$) result!
- Over year: earth moves through gradient

$$\delta\alpha/\alpha \sim 10^{-20}$$

- Near-future clocks: can detect this

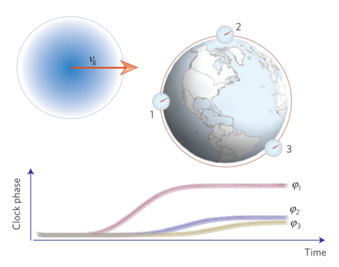
- Webb *et al.*, PRL **87**, 091301 (2001); **107**, 191101 (2011)

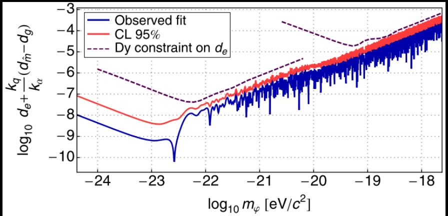
Transient/oscillating variation: dark matter

- Scalar-field DM with, $m_\phi \ll 1\,\text{eV}$
- Self-interaction $\implies$ clumps $\implies$ transients
- Otherwise $\implies$ $\phi = \phi_0 \sin(m_\phi t)$ $\implies$ oscillating

$$\mathcal{L}_{\rm int} = \pm \frac{\phi^2}{\Lambda_F^2} F^{\mu\nu} F_{\mu\nu} \pm \frac{\phi^2}{\Lambda_f^2} \bar{\psi}_f \psi_f$$

$$\frac{\delta\alpha}{\alpha} = \pm \frac{\phi^2}{\Lambda_F^2}, \qquad \frac{\delta m_f}{m_f} = \mp \frac{\phi^2}{\Lambda_f^2}$$

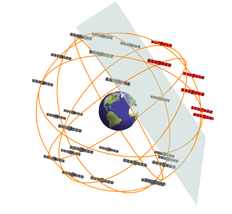


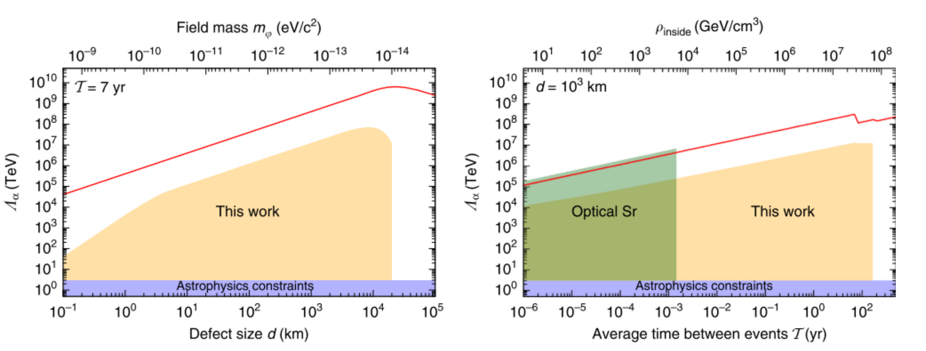


- Derevianko, Pospelov, Nat. Phys. **10**, 933 (2014)
- Hees *et al.*, Phys. Rev. Lett. **117**, 061301 (2016)
- Savalle, BMR *et al.*, Phys. Rev. Lett. **126**, 051301 (2021)

GPS: 50,000 km DM observatory

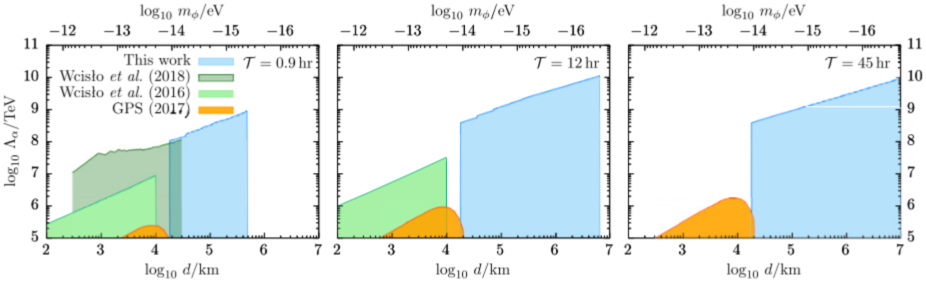
- 32 satellite clocks (Rb/Cs)
- $\sim$ 16 years of high-quality data
- Correlated, directional signal $v_g \sim 300\,\mathrm{km/s}$
- BMR *et al.*, Nature Comm. **8**, 1195 (2017)
- Wcisło *et al.*, Nature Astro. **1**, 0009 (2016)





European fibre-linked optical clock network

- Optical clocks: 10^{-16} (GPS: 10^{-12})
- Much less data $\sim$ hours (GPS: decade)
- Best constraints on $\sim$hour–day transient variation of α
- Complement: different parameter space

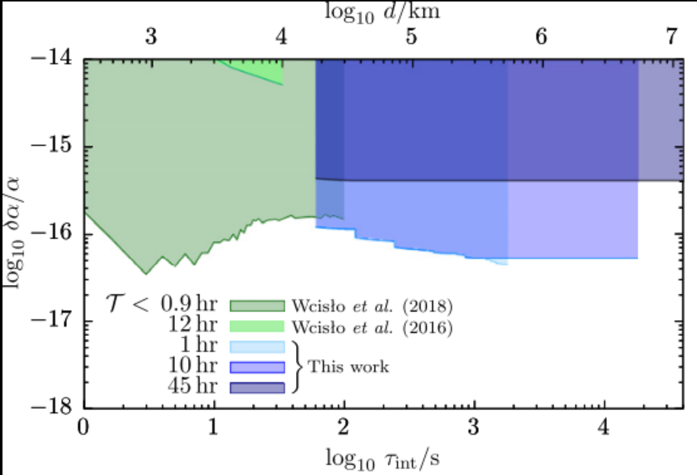


- BMR *et al.*, New J. Phys. **22**, 093010 (2020)

Extra

European fibre-linked optical clock network

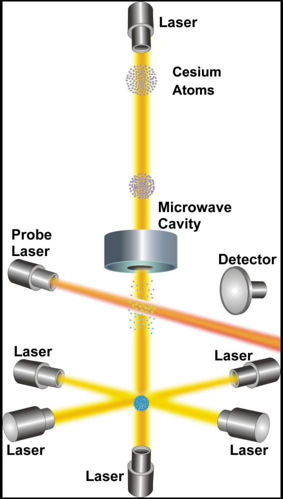
- Best constraints on transient variation of α



- BMR *et al.*, New J. Phys. **22**, 093010 (2020)

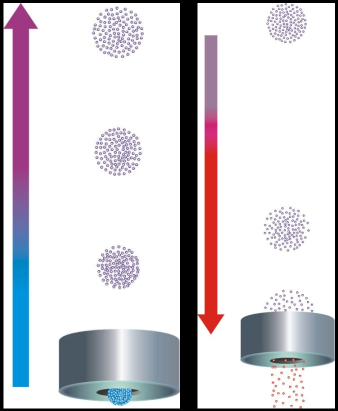
Clock operation: Microwave fountain clock

- 1. Cooling and/or trapping
- 2. State preparation: Ensure atoms in state $|A\rangle$
- 3. Interrogation: excite clock transition $|A\rangle \rightarrow |B\rangle$
- 4. Detection: measure population of $|B\rangle$

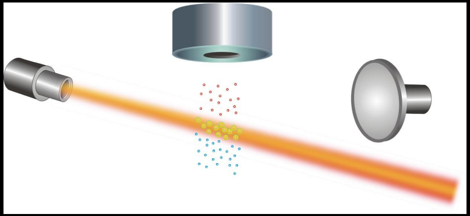


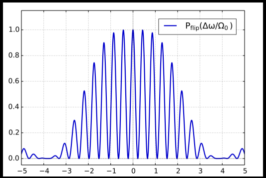
NIST: nist.gov/news-events/news/1999/12/nist-f1-cesium-fountain-clock

Clock operation: Microwave fountain clock - details



NIST: nist.gov/news-events/news/1999/12/nist-f1-cesium-fountain-clock



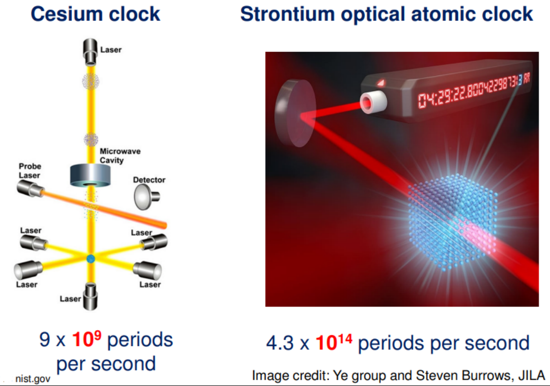


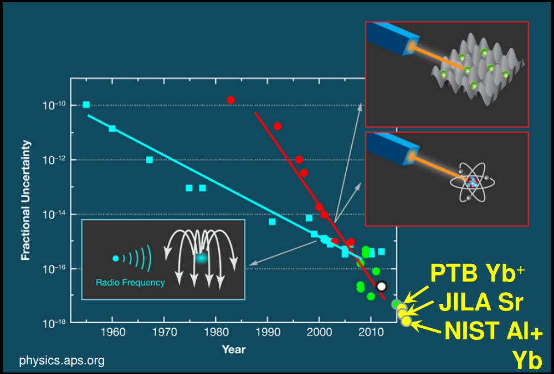
$$|A\rangle \rightarrow c_A|A\rangle + c_B|B\rangle$$

Detect population of $|B\rangle$: maximum fluorescence

Ramsey–Bordé interferometry or the separated oscillating fields method

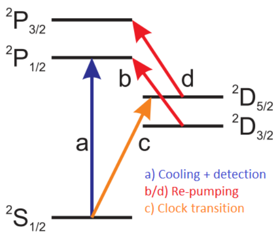
Optical vs. microwave clocks



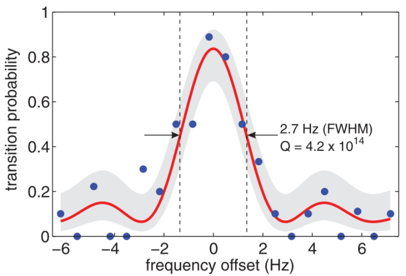


Clock operation: Typical optical clock

- 1. Cooling and/or trapping
- 2. State preparation: Ensure atoms in state $|A\rangle$
- 3. Interrogation: excite clock transition $|A\rangle \to |B\rangle$
- 4. Detection: measure population of $|B\rangle$



Ludlow 2015



Chou 2010

- If limited by quantum projection noise:

$$\sigma_y(\tau) = \frac{\delta f}{f_0 \sqrt{N}} \sqrt{\frac{T_{\text{cycle}}}{\tau}}$$

- This example: Al^+ clock: $f_0 \approx 1121.02\,\text{THz}$